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1983 International Intercomparison of Nuclear Accident Dosimetry Systems at Oak Ridge National Laboratory

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TABLE OF CONTENTS

LIST OF TABLES

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1983 INTERNATIONAL INTERCOMPARISON OF NUCLEAR ACCIDENT DOSIMETRY SYSTEMS AT OAK RIDGE NATIONAL LABORATORY

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Highlights

An international intercomparison of nuclear accident dosimetry systems was conducted during September 12-16, 1983, at Oak Ridge National Laboratory (ORNL) using the Health Physics Research Reactor operated in the pulse mode to simulate criticality accidents. This study marked the twentieth in a series of annual accident dosimetry intercomparisons conducted at ORNL. Participants from ten organizations attended this intercomparison and measured neutron and gamma doses at area monitoring stations and on phantoms for three different shield conditions. Results of this study indicate that foil activation techniques are the most popular and accurate method of determining accident-level neutron doses at area monitoring stations. For personnel monitoring, foil activation, blood sodium activation, and thermoluminescent (TL) methods are all capable of providing accurate dose estimates in a variety of radiation fields. All participants in this study used TLD's to determine gamma doses with very good results on the average. Chemical dosemeters were also shown to be capable of yielding accurate estimates of total neutron plus gamma doses in a veriety of radiation fields. While 83% of all neutron measurements satisfied regulatory standards relative to reference values, only 39% of all gamma results satisfied corresponding guidelines for gamma measurements. These results indicate that continued improvement in accident dosimetry evaluation and measurement techniques is needed.

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INTRODUCTION

An international intercomparison of nuclear accident dosimetry (NAD) systems was conducted at Oak Ridge National Laboratory's (ORNL) Dosimetry Applications Research (DOSAR) Facility during September 12-6, 1983. This study marked the twentieth in a series[1-5] of annual NAD intercomparisons conducted at ORNL. In recognition of this event, the International Atomic Energy Agency (IAEA) supported the participation of several international criticality accident dosimetrists in this study.

The intercomparison program is included in Appendix A of this report. The week-long study included experimental measurements, lectures, discussions, and demonstrations related to criticality accident dosimetry. During the experimental measurements, participants estimated neutron and gamma doses greater than 0.18 Gy (18 rads) at area monitoring stations (air stations) and on phantoms using the Health Physics Research Reactor (HPRR)[6] operated in the pulse mode to simulate criticality accidents. These results were compared to those of other participants who made measurements under identical conditions and to reference doses provided by the DOSAR staff. Lectures and discussions concerned performance characteristics of accident dosimetry systems, IAEA activities in criticality safety, medical aspects of radiation accidents, radiation dose determination based on chromosome aberrations, requirements and problems associated with criticality accident monitoring, and the future of accident dosimetry. Demonstrations were also given for foil, hair, and blood sodium activation analysis.

PARTICIPATION

Individual participants in this intercomparison, their affiliations, mailing addresses, and abbreviations used in this report to identify them are listed in Appendix B. A total of seventeen people from ten different organizations participated in this study with seven agencies reporting final results.

DESCRIPTION OF EXPERIMENTS

Table 1 is a summary of experimental conditions for this study. Three nuclear criticality accidents with yields on the order of 10^{16} fissions were simulated by operating the HPRR in the pulse mode. Neutron energy spctra and neutron-to-gamma dose ratios were varied among the pulses by operating the reactor unshielded, shielded with 13-cm of steel, and shielded with 20-cm of concrete. The fission yields shown in Table 1 provided neutron and gamma doses greater than or equal to 0.18 Gy.

Dosemeters were mounted on ring stands for air station measurements and on BOMAB[7] phantoms for personnel monitoring. Air stations and phantom centerlines were located 3 m from the reactor vertical centerline. A total of three phantoms were used - 2 filled with tap water and one filled with a saline solution with a sodium concentration approximating that found in human blood (1.5 mg/ml). The irradiated saline solution was made available to participants after each pulse for neutron dose measurements based on sodium activation analysis.[7-8]

DOSEMETERS USED IN THE INTERCOMPARISON

A brief description of the types of radiation dosemeters used in this study and the abbreviations used to identify them are given below. Neutron measurements were made using activation foils, thermoluminescent dosemeters (TLD's), and activated blood sodium. All gamma measurements were made with TLD systems - either TLD-700 (^7LiF) or $CaSO_4$ phosphors. A chemical dosimetry system[9] was also used to measure total neutron plus gamma doses at air stations and on phantoms. Detailed descriptions of nuclear accident dosimetry systems and methods are available in the literature [10-11].

Neutron Dosemeters

1. Foil Activation Systems (Act) - Some materials (e.g., gold, copper, indium, sulfur) become radioactive when exposed to neutrons. By measuring the activity of the exposed foils, neutron fluences over differential energy ranges can be estimated for the incident spectrum. Associated neutron doses can be obtained by applying fluence-to-dose conversion factors to the estimated fluences and summing over the range of energies encompassed by the activaton foils. Some activation systems also use foils made of fissionable materials (e.g., plutonium, neptunium, uranium) which have fission cross sections with thresholds at different neutron energies. These systems are called Threshold Detector Units (TDU's) and are generally used for area monitoring.

2. Thermoluminescent Dosemeters - Two types of thermoluminescent material (chips), one sensitive to gammas (^7LiF), and the other sensitive to neutrons and gammas (^6LiF), are simultaneously exposed to the simulated nuclear accident radiation fields. The response due to neutrons can be determined after both chips are analyzed. Various shields and absorbers are often placed near the chips to limit their exposure from a given direction to a selected range of neutron energies.

3. Blood Sodium Activation (NaACT) - Samples from irradiated, saline-filled phantoms are analyzed for ^{24}Na activity by any of a variety of counting techniques. The dose received by a phantom is proportional to the activity per unit volume of solution and the orientation of the phantom.

Gamma Dosemeters

All gamma dosemeters used in this study consisted of either TLD-700 or $CaSO_4$ thermoluminescent materials. When thermoluminescent phosphors are irradiated, metastable states are produced and, upon heating, light is emitted in proportion to the absorbed dose.

Chemical Dosemeters

Total neutron plus gamma dose measurements were performed using personnel accident dosemeter type DL-M3[9] which is based on the CET (chlorobenzene-ethanol-2,2,4-trimethylpentane) chemical system. After irradiation and preparation, the dosemeters are read by visual colorimetry.

REFERENCE DOSIMETRY

Reference neutron and gamma doses in air and on phantoms are given in Tables 2 and 3, respectively. Reference neutron doses given in Table 2 for air stations were obtained using fission yields determined by measuring the ^{32}P beta activity in a 22 gram sulfur pellet located at a fixed position near the reactor core and calculated dose-per-fission conversion factors at 3 m from the reactor for the various HPRR spectra[13]. Reference neutron doses in air are given in terms of wet tissue kerma[11] and element 57 absorbed dose with the capture gamma component excluded. Element 57 refers to the central volume element of a tissue-equivalent cylindrical phantom used to calculate the average absorbed dose in a volume element per unit incident neutron fluence[14]. Neutron dose in volume element 57 is the highest for all volume elements in the phantom and represents the expected maximum measured value for each exposure in this study. Reference gamma doses in air were obtained by dividing neutron kerma in air by the neutron-to-gamma dose ratio at 3 m from the reactor. The neutron-to-gamma dose ratio is based on measured results from the first nineteen NAD intercomparison studies.

The reference neutron and gamma doses on phantoms given in Table 3 were calculated by multiplying doses in air by appropriate air-to-phantom conversion factors developed from measured results of the first nineteen NAD intercomparisons. These factors were applied only to neutron kerma and gamma dose values since element 57 dose represents the absorbed dose in a particular volume element of a tissue equivalent phantom. Discussions among participants at this intercomparison resulted in the recommendation that neutron doses be reported in terms of wet tissue kerma at air stations and in terms of element 57 dose for phantoms. These conventions will be used in this report to specify reference values for analysis of reported results. For additional information, reference neutron doses in terms of wet tissue kerma are included in Table 3 for phantoms.

MEASUREMENT RESULTS AND ANALYSIS

Tables 4 through 9 summarize results of measurements reported by individual participants for this intercomparison. Each table gives the number, fission yield, and shield condition for the particular pulse plus the agency identification as shown in Appendix B, neutron dose, gamma dose, and basis for dose estimates. Tables 4-6 summarize data for measurements at air stations for pulses 1-3, respectively, while Tables

7-9 present results of phantom measurements. In addition to reported results, reference neutron and gamma doses are included for each irradiation. Dosemeter performance characteristics described in the following text are based on data presented in these tables.

A summary of results of neutron dose measurements at air stations and on phantoms is given in Table 10. Information presented in this table includes the average measured dose, experimental standard deviation about the mean, and the number of reported measurements for foil activation, sodium activation, TLD, and the collection of all neutron dosemeter types. Reference doses based on wet tissue kerma for air stations and on the element 57 convention for phantoms are also given. Foil activation systems were by far the most popular type of neutron accident dosemeters for air station and phantom measurements.

Table 11 gives average measured neutron doses normalized to the reference values and associated percent standard deviations (in parenthesis) based on data shown in Table 10. Normalized dose indicates the accuracy of the mean of a set of measurements relative to the reference value. Percent standard deviation about the mean is an indication of precision and reflects agreement among individual measurements of the same dose.

Analysis of normalized values for the composite of all measurements (column labeled "All" in Table 11) indicates that, on the average, measured neutron doses were within 20% of reference values for all spectra. For each pulse, average neutron doses measured at air stations were more accurate than corresponding results measured on phantoms. For each set of measurements (air station and phantom), the softest neutron energy spectrum (concrete) provided the least accurate results with magnitudes of average normalized results increasing with increasing spectrum softness (i.e., decreasing mean energy). These trends have been observed in previous intercomprisons.[1-5] Percent standard deviations about the mean ranged from 8 to 15% (average = 12%) for air station measurements and from 14 to 20% (average = 17%) for phantom measurements. At air stations and on phantoms, neutron measurements were more precise for unshielded pulses (average = 11%) than for shielded pulses (average = 16%). For each spectrum, air station measurements were more precise than corresponding measurements made on phantoms. Overall, precisions indicated for neutron measurements in this study were much lower than those obtained in prior ORNL intercomparisons.[1-5]

With regard to individual neutron dosimetry systems, most agencies used foil activation methods to determine doses at air stations and on phantoms. Average results were within 6% of reference values for air station measurements and within 24% of references for phantom results. Measurement precision for foil activation systems ranged from 9-13% and from 15-23% of the means for air station and phantom results, respectively. Qualitative performance of foil activation dosemeters was similar to that observed for the composite of all measurements.

Since only two agencies used simulated blood sodium activation and only one organization used TLD's to determine neutron doses, a detailed analysis of results obtained using these techniques is not possible. However, results obtained using these methods indicate that both techniques can provide accurate neutron dose estimates for the conditions encountered in this study. Blood sodium activation results ranged from 0.98 to 1.20 times reference values for the three spectra. The TLD-measured neutron doses varied from 0.73 to 1.10 times reference values with the air station measurement being within 5% of the reference.

Table 12 shows average gamma dose measurements at air stations and on phantoms, associated standard deviations from the mean, the number of reported results (in parenthesis), reference dose values, and measured and reference neutron-to-gamma dose ratios (D_n/D_γ) at air stations. All reported gamma dose measurements were made with TLD-700 or $CaSO_4$ phosphors as indicated in Tables 4-9. Measured neutron-to-gamma dose ratios at air stations are within one experimental standard deviation of the reference values for each spectrum.

Average measured gamma doses normalized to the reference values and associated percent standard deviations from the mean (in parenthesis) for air station and phantom measurements are given in Table 13. Average measured results were within 17% of the reference values for all spectra and ranged from 0.83 to 1.12 times the references for air station and phantom measurements. Associated percent standard deviations ranged from 13 to 65% of the means and were higher than corresponding neutron results obtained for each spectrum. The least accurate gamma dose estimates were obtained for the steel-shielded spectrum (pulse 2) which had the highest neutron-to-gamma dose ratio of the spectra considered in this study.

Table 14 summarizes total neutron plus gamma doses determined using DL-M3 accident dosemeters which are based on the CET chemical system.[9] The table gives reported, reference, and normalized results for air station and phantom measurements. All results were within 23% of reference values with the most accurate results (within 4% of reference) obtained for the unshielded pulse (hardest neutron spectrum). Least accurate results (23% of reference) were obtained for the softest neutron spectrum (pulse 3, concrete shield). Measurement accuracies for corresponding air station and phantom results were similar for all three pulses.

Measured and reference phantom-to-air station dose ratios for neutrons and gammas are given in Table 15 for the three spectra considered in these studies. Reference values are based on results obtained during the previous nineteen intercomparisons. For neutrons and gammas, measured results were well within one experimental standard deviation of reference values. Neutron doses measured on phantoms are greater than those measured at air stations because of reflected neutrons. Gamma doses are larger on phantoms primarily because of contributions from the $^{1}H(n,\gamma)^{2}H$ reaction in the phantom filled with water.

DOSEMETER PERFORMANCE RELATIVE TO REGULATORY CRITERIA

Criticality accident dosimetry guidelines[15-16] suggest accuracies of $\pm$ 25% for neutron dose and $\pm$ 20% for gamma dose. Table 16 summarizes the performance of all neutron and gamma measurements at air stations and on phantoms relative to these standards. Considering all measurements, 83% of the neutron results and only 39% of the gamma results met the guidelines. For neutrons, more air station measurements (average = 93%) satisfied the criteria than did measurements on phantoms (average = 75%). More gamma measurements at air stations (average = 47%) satisfied the criteria than on phantoms (average = 33%). These results are consistent with those encountered in prevous intercomparisons.[1-5]

CONCLUSIONS

Results of this international intercomparison study indicate that foil activation techniques continue to be the most popular and accurate method for determining neutron doses at area monitoring stations for accident-level doses (> 0.1 Gy) For personnel monitoring, foil activation systems, TLD systems, and blood sodium activation analysis are all capable of providing accurate neutron dose estimates in a variety of radiation fields. All participants in this study used TLD's to determine gamma doses with very good results on the average. Chemical dosemeters were also shown to be capable of yielding total neutron plus gamma dose estimates within 23% of reference values at air stations and on phantoms in a variety of radiation fields. While 83% of all neutron measurements satisfied regulatory guidelines relative to reference values, only 39% of all gamma results satisfied corresponding standards for gamma measurements. These results indicate that continued improvement in accident dosimetry evaluation and measurement techniques is needed.

RECOMMENDATIONS

Discussions conducted among participants in this intercomparison, which represented several internationally recognized authorities in the field of accident dosimetry, resulted in the following recommendations:

1. There is still no general standard on what neutron dose convention should be used to report accident doses. Lectures and discussions on this topic led to the consensus that wet tissue kerma should be used for results obtained at area monitoring stations and the element 57 convention should be used for personnel or phantom results.

In any case, the convention associated with the reported result should be explicitly included with the numerical data.

2. The need for continuing the ORNL criticality accident dosimetry intercomparison program was emphasized. There is presently no other periodic accident dosimetry intercomparison study offered anywhere else in the world. This program has been and will continue to be very valuable to participants in testing and developing their accident dosimetry systems.

3. Although the frequency of actual criticality accidents has significantly decreased in recent years, there is a need for a means to train dosimetrists in accident dosimetry principles and methods. In response to this need, the DOSAR staff will continue to periodically offer an accident dosimetry training course which includes lectures and laboratory experiments on accident dosimetry techniques, criticality alarm monitoring, medical aspects of radiation accidents, and chromosome aberration analysis.

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Table 1. Summary of experimental conditions[a]

Pulse No.	Date	Eastern Daylight Time	Pulse yield,[b] 10^{16} fissions	Shield	Reactor to shield distance, m
1	9/13/83	1016	9.37	None	-
2	9/14/83	1015	7.86	13-cm steel	2
3	9/15/83	1001	5.89	20-cm concrete	1

[a]Dosemeters at area monitoring stations were located 3 m from the center of the HPRR. Centerlines of phantoms on which personnel dosemeters were exposed were 3 m from the HPRR centerline.

[b]Based on sulfur pellet activation analysis.

Table 2. Reference neutron and gamma doses at air stations

Pulse no.	Shield	Pulse yield, 10^{16} fissions	Neutron dose, 10^{-2} Gy[a] Kerma	Neutron dose, 10^{-2} Gy[a] Element 57	Neutron-to-gamma dose ratio[b]	Gamma dose 10^{-2}Gy[c]
1	None	9.37	375	430	6.1	62
2	13-cm steel	7.86	137	141	7.8	18
3	20-cm concrete	5.89	51	59	2.6	20

[a]Calculated dose at 3 m from the reactor centerline based on HPRR reference dosimetry document ORNL/TM-7748. Units are 10^{-2} Gy (1 rad).

[b]Dose ratio at 3 m from the reactor centerline based on measured results of the first nineteen nuclear accident dosmetry intercomparison studies.

[c]Neutron kerma divided by the neutron-to-gamma dose ratio.

Table 3. Reference neutron and gamma doses on phantoms

Pulse no.	Neutron air-to-phantom conversion[a]	Neutron dose, 10^{-2}Gy Kerma[b]	Neutron dose, 10^{-2}Gy Element 57	Gamma air-to-phantom conversion[a]	Gamma dose 10^{-2}Gy[b]
1	1.05	394	430	1.70	105
2	1.19	163	141	2.33	42
3	1.20	61	59	1.62	33

[a]Ratio of phantom-tc-air dose based on measured results from the first nineteen nuclear accident dosimetry intercomparison studies.

[b]Product of conversion factor times the dose in air given in Table 2.

Table 4. Measurements at air stations for pulse no. 1

Yield: 9.37 (10^{16}) fissions

Shield: None

Group	Neutron dose, 10^{-2}Gy[a]	Gamma dose, 10^{-2}Gy	Detector system	
			Neutron	Gamma
Reference	375	62	-	-
Reference	430[b]	-	-	-
BARC	305	44	Act[c]	TLD-$CaSO_4$
CRIP	343	27	Act/track	TLD-700
DOSAR	365	66	Act	TLD-700
GAT	360	76	Act	TLD-700
GAT	355	-	TLD	-
RBI	421[d]	-	Chemical	-
RFP	389	79	Act	TLD-$CaSO_4$

[a]Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2}Gy (1 rad).

[b]Element 57 dose with H(n,γ) component excluded.

[c]Neutron activation foils.

[d]Total neutron plus gamma dose.

Table 5. Measurements at air stations for pulse no. 2

Yield: 7.86 (10^{16}) fissions

Shield: 13-cm steel

Group	Neutron dose, 10^{-2}Gy[a]	Gamma dose, 10^{-2}Gy	Detector system	
			Neutron	Gamma
Reference	137	18	-	-
Reference	141[b]	-	-	-
BARC	121	13	Act[c]	TLD-$CaSO_4$
CRIP	169	14	Act/track	TLD-700
DOSAR	136	14	Act	TLD-700
GAT	122	15	Act	TLD-700
RBI	127[d]	-	Chemical	-
RFP	121	18	Act	TLD-$CaSO_4$

[a]Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2}Gy (1 rad).

[b]Element 57 dose with H(n,γ) component excluded.

[c]Neutron activation foils.

[d]Total neutron plus gamma dose.

Table 6. Measurements at air stations for pulse no. 3

Yield: 5.89 (10^{16}) fissions

Shield: 20-cm concrete

Group	Neutron dose, 10^{-2}Gy[a]	Gamma dose, 10^{-2}Gy	Detector system	
			Neutron	Gamma
Reference	51	20	–	–
Reference	59[b]	–	–	–
BARC	58	15	Act[c]	TLD-$CaSO_4$
CRIP	46	12	Act/track	TLD-700
DOSAR	44	20	Act	TLD-700
GAT	56	22	Act	TLD-700
RBI	55[d]	–	Chemical	–
RFP	60	43	Act	TLD-$CaSO_4$

[a] Neutron doses represent wet tissue kerma unless otherwise indicated and are given in units of 10^{-2}Gy (1 rad).

[b] Element 57 dose with H(n,γ) component excluded.

[c] Neutron activation foils.

[d] Total neutron plus gamma dose.

Table 7. Measurements on phantoms for pulse no. 1

Yield: 9.37 (10^{16}) fissions

Shield: None

Group	Neutron dose, 10^{-2}Gy[a]	Gamma dose, 10^{-2}Gy	Basis for estimates	
			Neutron	Gamma
Reference	430	105	-	-
BARC	477[b]	96	Act[c]	TLD-$CaSO_4$
CRIP	383	73	Act/track	TLD-700
DOSAR	417	104	NaAct[d]	TLD-700
EOS-ORNL	361	58	Act	n/γ ratio
GAT	332	130	Act	TLD-700
GAT	315	-	TLD	-
GAT	428	-	NaAct	-
RBI	524[e]	-	Chemical	-
RFP	360	157	Act	TLD-$CaSO_4$

[a]Neutron doses given in element 57 convention unless otherwise indicated and in units of 10^{-2}Gy (1 rad).

[b]Surface absorbed dose = recoils + protons + H(n,γ).

[c]Neutron activation foils.

[d]Blood sodium activation.

[e]Total neutron plus gamma dose.

Table 8. Measurements on phantoms for pulse no. 2

Yield: 7.86 (10^{16}) fissions

Shield: 13-cm steel

Group	Neutron dose, 10^{-2}Gy[a]	Gamma dose, 10^{-2}Gy	Basis for estimates	
			Neutron	Gamma
Reference	141	42	-	-
BARC	175[b]	30	Act[c]	TLD-$CaSO_4$
CRIP	175	22	Act/track	TLD-700
DOSAR	166	27	NaAct[d]	TLD-700
EOS-ORNL	133	53	Act	TLD-700
GAT	185	40	Act	TLD-700
GAT	175	-	NaAct	-
GAT	428	-	NaAct	-
RBI	170[e]	-	Chemical	-
RFP	114	37	Act	TLD-$CaSO_4$

[a]Neutron doses given in element 57 convention unless otherwise indicated and in units of 10^{-2}Gy (1 rad).

[b]Surface absorbed dose = recoils + protons + $H(n,\gamma)$.

[c]Neutron activation foils.

[d]Blood sodium activation.

[e]Total neutron plus gamma dose.

Table 9. Measurements on phantoms for pulse no. 3

Yield: 5.89 (10^{16}) fissions

Shield: 20-cm concrete

Group	Neutron dose, 10^{-2}Gy[a]	Gamma dose, 10^{-2}Gy	Basis for estimates	
			Neutron	Gamma
Reference	59	33	-	-
BARC	89[b]	27	Act[c]	TLD-$CaSO_4$
CRIP	51	26	Act/track	TLD-700
DOSAR	66	28	NaAct[d]	TLD-700
EOS-ORNL	70	18	Act	TLD-700
GAT	65	42	TLD	TLD-700
RBI	71[e]	-	Chemical	-
RFP	83	83	Act	TLD-$CaSO_4$

[a]Neutron doses given in element 57 convention unless otherwise indicated and in units of 10^{-2}Gy (1 rad).

[b]Surface absorbed dose = recoils + protons + H(n,γ).

[c]Neutron activation foils.

[d]Blood sodium activation.

[e]Total neutron plus gamma dose.

Table 10. Summary of results of neutron dose measurements at air stations and on phantoms

Pulse no.	Dosemeter location (spectrum)	Neutron dose, 10^{-2} Gy[a]				
		Activation[b]	Sodium[c]	TLD	All[d]	Reference
1	Air (bare)	352 ± 31 (5)[e]	-	355 (1)	353 ± 28 (6)	375
2	Air (steel)	134 ± 21 (5)	-	-	134 ± 21 (5)	137
3	Air (concrete)	53 ± 7 (5)	-	-	53 ± 7 (5)	51
1	Phantom (bare)	383 ± 56 (5)	422 ± 8 (2)	315 (1)	384 ± 54 (8)	430
2	Phantom (steel)	156 ± 31 (5)	170 ± 6 (2)	-	160 ± 26 (7)	141
3	Phantom (concrete)	73 ± 17 (4)	66 (1)	65 (1)	71 ± 14 (6)	59

[a]Values are average doses ± one standard deviation based on data shown in tables 4-6 (air) and tables 7-9 (phantoms). Wet tissue kerma convention is used for air station results and element 57 convention used for phantom measurements.

[b]Neutron activation foils.

[c]Blood sodium activation.

[d]Includes results for all dosemeter types.

[e]Number of measurements given in parenthesis.

Table 11. Normalized average measured neutron doses and percent standard deviations[a]

Pulse no.	Dosemeter location (spectrum)	Normalized neutron dose (percent standard deviation)[b]			
		Activation[c]	Sodium[d]	TLD	All[e]
1	Air (bare)	0.94(9)	-	0.95 (0)[f]	0.94 (8)
2	Air (steel)	0.98 (15)	-	-	0.98 (15)
3	Air (concrete)	1.04 (13)	-	-	1.04 (13)
1	Phantom (bare)	0.89 (15)	0.98 (2)	0.73 (0)[f]	0.89 (14)
2	Phantom (steel)	1.10 (20)	1.20 (4)	-	1.13 (16)
3	Phantom (concrete)	1.24 (23)	1.12 (0)[f]	1.10 (0)[f]	1.20 (20)

[a]Based on data shown in Table 10.

[b]Average reported measured dose divided by the reference value (percent of standard deviation about the mean).

[c]Neutron activation foils.

[d]Blood sodium activation.

[e]Includes results for all dosemeter types.

[f]Only one measurement reported for this pulse.

Table 12. Summary of results of gamma dose measurements at air stations and on phantoms

Pulse no.	Dosemeter location (spectrum)	Gamma dose, 10^{-2} Gy[a]		Dn/Dγ	
		TLD[b]	Reference	Measured[c]	Reference[d]
1	Air (bare)	58 ± 22 (5)[e]	62	6.1 ± 1.0	6.1
2	Air (steel)	15 ± 2 (5)	18	8.9 ± 1.2	7.8
3	Air (concrete)	22 ± 12 (5)	20	2.4 ± 0.5	2.6
1	Phantom (bare)	103 ± 36 (6)	105		
2	Phantom (steel)	35 ± 11 (6)	42		
3	Phantom (concrete)	37 ± 24 (6)	33		

[a]Values are average doses based on data shown in Tables 4-6 (air) and Tables 7-9 (phantoms) ± one standard deviation about the mean.

[b]All reported gamma measurements were made with TLD-700 or $CaSO_4$ phosphors.

[c]Average of all reported neutron kerma measurements divided by the average of all reported gama measurements ± one standard deviation.

[d]Data from Table 2 based on the first nineteen NAD studies.

[e]Number of reported results in parenthesis.

Table 13. Normalized average measured gamma doses and associated percent standard deviations[a]

Pulse no.	Shield	Dosemeter location	Normalized gamma dose (percent standard deviation)[b]
1	None	Air	0.94 (38)
2	Steel	Air	0.83(13)
3	Concrete	Air	1.10 (54)
1	None	Phantom	0.98 (35)
2	Steel	Phantom	0.83 (31)
3	Concrete	Phantom	1.12 (65)

[a]Based on data shown in Table 12.

[b]Average reported measured dose divided by the reference value (percent of standard deviation about the mean).

Table 14. Summary of measurements of total neutron and gamma doses using chemical dosemeters[a]

Pulse no.	Shield	Dosemeter location	Total dose, 10^{-2} Gy[b]		Normalized result[d]
			Reported[c]	Reference	
1	None	Air	421	437	0.96
2	Steel	Air	127	155	0.82
3	Concrete	Air	55	71	0.77
1	None	Phantom	524	535	0.97
2	Steel	Phantom	170	183	0.93
3	Concrete	Phantom	71	92	0.77

[a] Measurements made by the Rudes Boskovic Institute using DL-M3 accident dosemeters based on the CET chemical system

[b] Neutron plus gamma dose.

[c] Based on data shown in Tables 4-6 (air stations) and Tables 7-9 (phantoms).

[d] Reported dose divided by reference value. Reference neutron dose based on wet tissue kerma for air stations and on element 57 for phantoms.

Table 15. Comparison of doses measured on phantoms with those measured at air stations

Pulse No.	Shield	Ratio of phantom dose to air station dose			
		Neutron		Gamma	
		Measured[a]	Reference[b]	Measured[c]	Reference[b]
1	None	1.09 ± 0.21[d]	1.05	1.78 ± 0.34	1.70
2	Steel	1.19 ± 0.32	1.19	2.33 ± 0.31	2.33
3	Concrete	1.34 ± 0.48	1.20	1.68 ± 0.57	1.62

[a]Based on data given in Table 10 for all reported measurements.

[b]Based on data obtained during the previous nineteen NAD intercomparisons.

[c]Based on data given in Table 12.

[d]Phantom dose divided by air station dose ± one standard deviation about the mean.

Table 16. Summary of final measured results relative to regulatory criteria

Pulse number	Dosemeter location (shield)	Neutron results: Number of measurements	Neutron results: Number meeting criterion[a]	Gamma Results: Number of measurements	Gamma Results: Number meeting criterion[a]
1	Air (none)	6	6 (100)[b]	5	1 (20)
2	Air (steel)	5	4 (80)	5	4 (80)
3	Air (concrete)	5	5 (100)	5	2 (40)
1	Phantom (none)	7	6 (86)	6	2 (33)
2	Phantom (steel)	7	5 (71)	6	2 (33)
3	Phantom (concrete)	6	4 (67)	6	2 (33)
Total		36	30 (83)	33	13 (39)

[a] Criteria presented in ANSI N 13.3 which suggest accuracies of $\pm$ 25% for neutron doses and $\pm$ 20% for gamma doses.

[b] Percent of reported results meeting criteria are given in parenthesis.

APPENDIX A

PROGRAM

TWENTIETH NUCLEAR ACCIDENT DOSIMETRY INTERCOMPRISON STUDY

September 12-16, 1983

Date	Time	Activity
September 12	9:30 AM	Welcome, R. O. Chester (ORNL)
	9:40	Orientation, C. S. Sims (ORNL)
	10:00	Review of the study program, R. E. Swaja (ORNL)
	10:30	Tour ot DOSAR Facility and HPRR
		LUNCH
	1:00 PM	Lecture: Nuclear Accident Dosimetry Intercomparison Studies Using the Health Physics Research Reactor - C. S. Sims (ORNL)
	2:00	Lecture: IAEA Activities in Accident Dosimetry and Criticality Safety - F. N. Flakus (IAEA)
	3:00	Discussion: Format and objectives of the intercomparison
	3:30	Preparation for Pulse No. 1
	6:00	Evening social
September 13	8:30 AM	Final setup of dosimetry for Pulse No. 1
	9:00	Observation of pulse operation of HPRR
	10:00	Pulse No. 1 (unshielded)
	10:30	Lecture: Requirements and Problems associated with Criticality Accident Monitoring at Participating Facilities - Speakers selected from among participants
	11:30	Collect dosimeters
		LUNCH
	1:00 PM	Analysis of data and preparation for Pulse No. 2 - Demonstration of foil activation analysis

Date	Time	Activity
September 14	8:30 AM	Final setup of dosimeters for Pulse No. 2
	8:45	Group photograph
	9:00	Tour of ORNL facilities
	10:00	Pulse No. 2 (13-cm steel shield)
	11:30	LUNCH
	1:00 PM	Analysis of data and preparation for Pulse No. 3 - Demonstration of hair and blood sodium activation analysis
September 15	8:00 AM	Final setup for Pulse No. 3
	9:00	Lecture: Medical Aspects of Radiation Accidents - R. C. Ricks (ORAU - REACTS)
		Pulse No. 3 (20-cm concrete)
	10:00	Lecture: Determination of Radiation Doses Based on Chromosome Aberrations - L. G. Littlefield (ORAU)
	11:00	Review data reporting requirements and collect dosimeters
		LUNCH
	1:00	Analysis of data
	6:30	Dinner for study participants at Piccolo's Restaurant in Knoxville
September 16	9:00 AM	Presentation of preliminary dose estimates and discussion of results
	10:00	Discussion: The future of accident monitoring and dosimetry
	11:00	Final critique

APPENDIX B

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